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Observation of single-electron pump operation with one ac gate bias in phosphorous-doped Si wires

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1. Introduction

Coulomb blockade (CB) devices with multiple tunnel junctions (MTJs) have attracted much interest in the last decade from the viewpoint of low-power consumption and functionality.[1-3] Our purpose was to investigate the possibility of realizing single-electron pumps in random MTJ systems in which electrons could be transferred one-by-one between source and drain even against the applied potential. We observed for the first time the transfer of one electron per period of one gate pulse applied to a Si wire with islands formed by potential modulation due to doping.[4] We emphasize that our device works as a single-electron pump with single ac gate bias, while typical single-electron pump circuits require at least two ac gate biases with a well-defined phase shift.[1,2] This single-electron pump operation in devices comprising naturally formed islands using only one ac gate bias would greatly simplify circuit designs.

2. Device structure

Metal-oxide-semiconductor field-effect transistors (MOSFETs) were fabricated on silicon-on-insulator (SOI) substrates. As shown in Fig. 1, the device channel is a Si wire with typical length, width and height of 100 nm, 10 nm and 10 nm, respectively. The wire was phosphorous-doped with a concentration of about 1×10^{18} cm^{-3}. The potential modulation induced by the non-uniform doping distribution along the Si wire leads to the natural formation of multiple islands with capacitances in the aF range.[4] The source, drain and the single top gate are fabricated of phosphorous-doped poly-Si.

3. Results and discussion

Fig. 2 shows the drain current through the device as a function of the dc gate voltage at a typical measurement temperature of 5.5 K and a drain-source bias V_d=10 mV. The features of this curve prove the existence of multiple tunnel junctions within the wire, as expected due to doping.[4]

Under dc gate voltage operation, charge transfer between source and drain is forbidden by the Coulomb blockade effect at around V_d=0 V (dashed curves in Figs. 3(a) and (b)). However, when an rf signal is applied to the gate, non-zero drain current flows even at zero bias for certain values of the gate offset voltage V_{g0} (as indicated at V_d=0 V for the solid curves in Figs. 3(a) and (b)). The applied signal can be described as: $V_g^{rf}=V_{g0}\pm\Delta V_g$, with a typical amplitude ΔV_g=50 mV. The pump operation is confirmed by the fact that the source-drain current can be alternatively positive or negative depending on the V_{g0}, as illustrated in Fig. 3(c). Fig. 3(d) shows the dependence of the current measured at V_d=0 V on the pulse frequency. These results indicate that electrons are transferred one-by-one during each cycle of gate voltage, confirming that our single-gated MTJ device works as a single-electron pump. The departure of the experimental current at V_d=0 V from the ideal single-electron current ($I_d^{exp}<I_d^{se}=ef$) may be ascribed to missed transitions during some of the cycles at higher frequencies. We have investigated the pump operation only for frequencies lower than 1 MHz and it can be seen that, by decreasing the frequency, the accuracy of single-electron transfer is increased. The rough proportionality of the current level to the frequency is further evidence of the pump operation.[1,2]

In principle, pump operation requires that multiple clock signals are applied to the device.[1,2] Our experimental results are obtained by applying only one ac gate bias on an array of Coulomb islands naturally formed due to the doping distribution. In Fig. 4(a), these islands are depicted as dashed circles enclosed by tunnel junctions with capacitances C_j. The gate is coupled to each island ideally through gate capacitances C_{gi}. One possible model that can explain the observed behavior is based on non-uniform resistive coupling of the gate to the channel. The stray resistances may split the ac signal into multiple clock signals with certain phase difference, as required for the pump operation (equivalent circuit of a typical single-electron pump is shown in Fig. 4(b)). Another possible explanation may derive from non-uniform gate capacitance distribution,[5] but further investigations are necessary in this direction. We observed that Si MTJ devices can work as single-electron pumps and the striking feature is that this operation requires only one ac gate bias.

4. Conclusions

We observed that MTJ devices are a candidate for transferring electrons one-by-one even against the source-drain potential using only one clock signal. This simplifies the single-electron pump circuit, opening a wide variety of applications.

References

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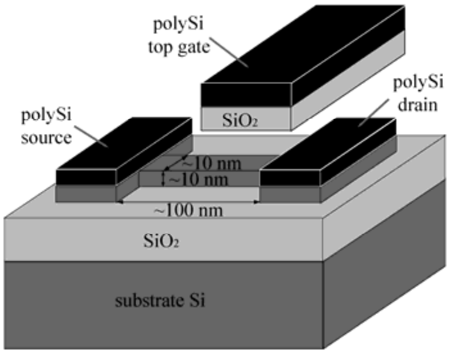

Fig. 1 MOSFET fabricated on a SOI structure. The Si wire typically has the length, width and height of ~100 nm, ~10 nm and ~10 nm, respectively. Poly-Si gates cover the source and drain regions and the wire region.

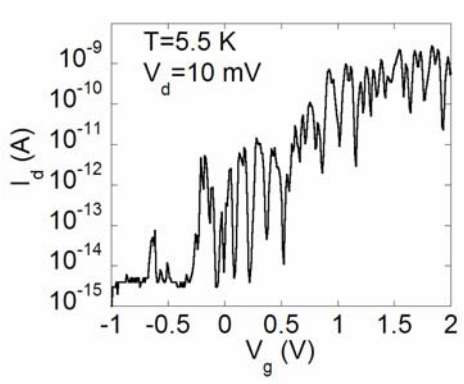

Fig. 2 Drain current as a function of dc gate voltage at 5.5 K and 10 mV bias. The irregular peak structure indicates that multiple islands are formed within the wire .

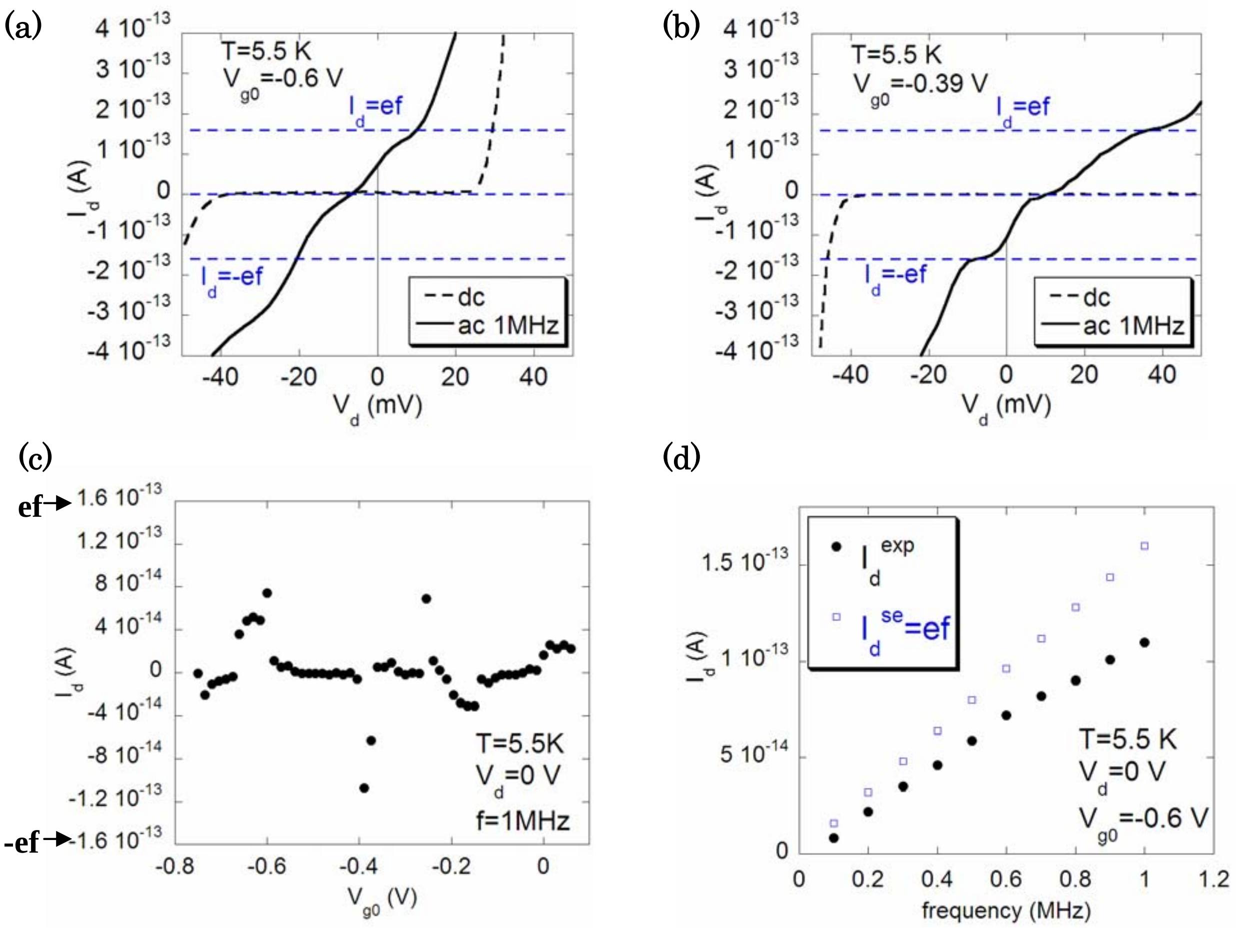

Fig. 3 I_d-V_d characteristics at 5.5 K for: (a) V_{g0}=-0.6 V and (b) V_{g0}=-0.39 V, respectively, for dc (dashed curves) and ac (solid curves) operation. Dashed lines correspond to I_d=ef at f=1 MHz. (c) Alternative positive and negative currents flow even at V_d=0 V. (d) Frequency dependence of the drain current (solid dots) as compared to the expected single-electron current.

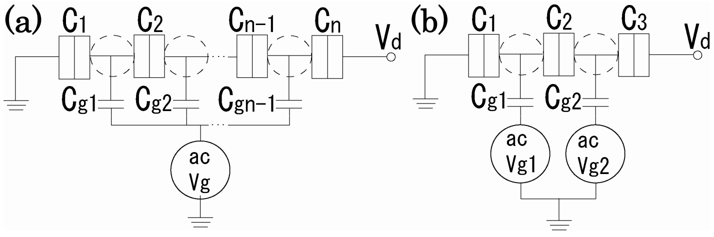

Fig. 4 (a) Equivalent circuit of a one-dimensional MTJ device. Multiple islands (dashed circles) and tunnel junctions of capacitances C_j are formed by doping. One ac gate clock is applied on the entire array through gate capacitances C_{gi}. (b) ordinary single-electron pump circuit.